Recent Progress on QPS

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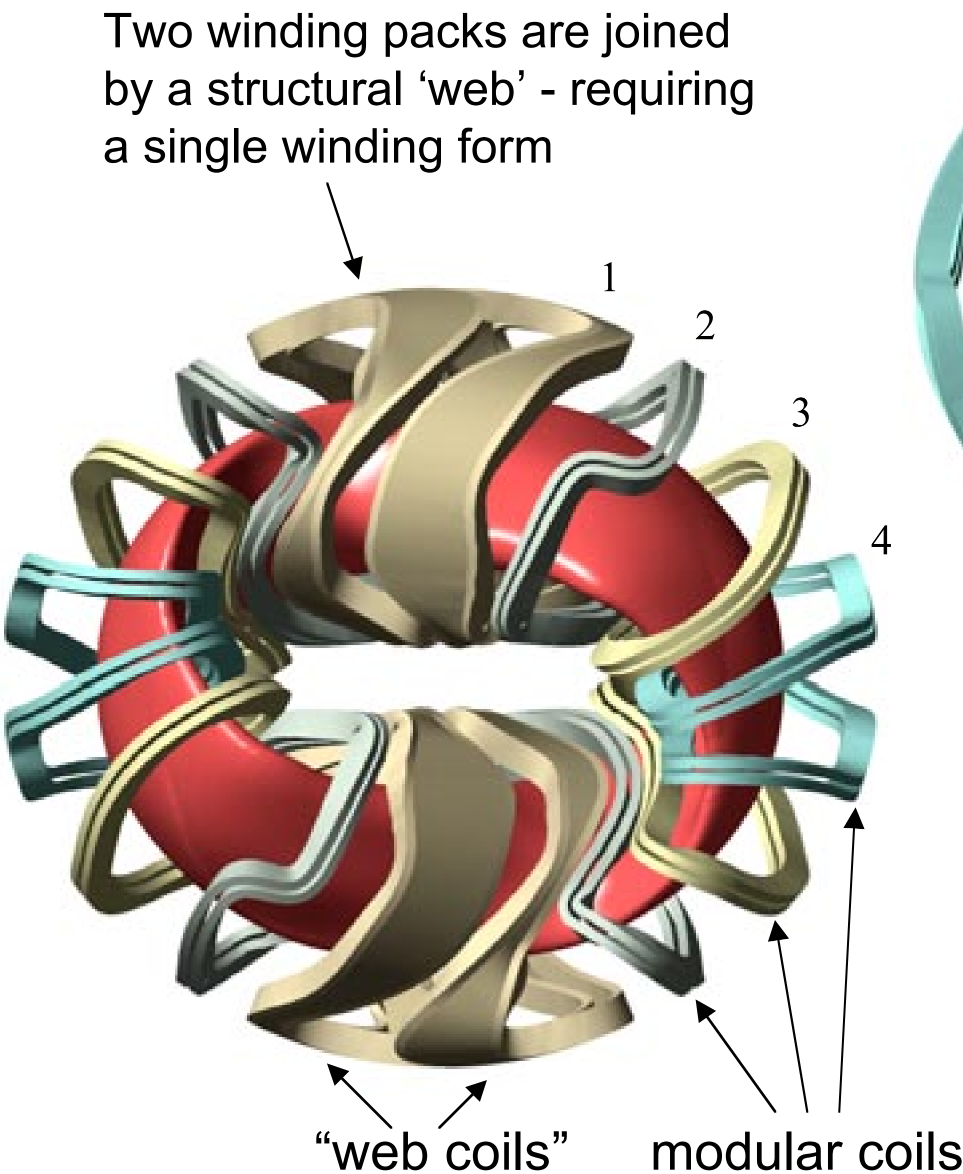
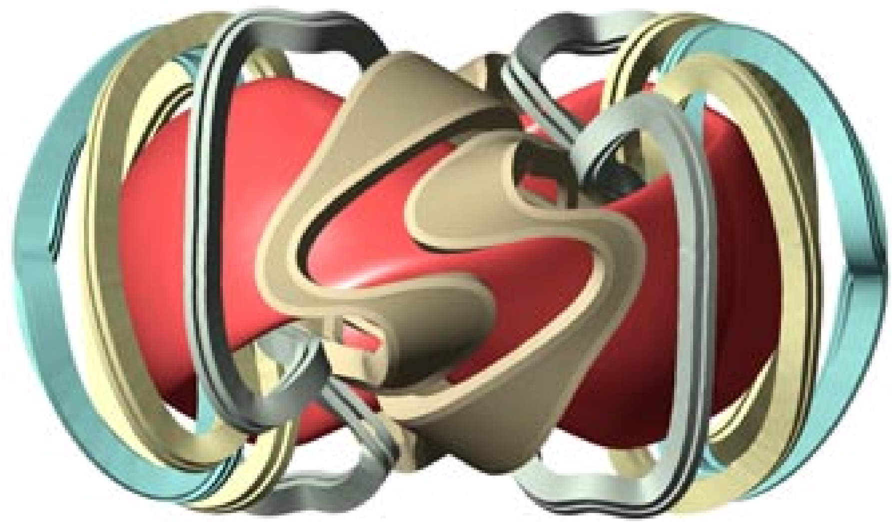
- Improved coil design (see recent Stellarator News article)
  - New flux surface optimization target
  - Reduced island size
  - Invariance of surface shape with β
  - Lower cost coils, developable coil winding surfaces
- Neoclassical viscosity/momentum conserving corrections to DKES
  - Recent formulation of H. Sugama, S. Nishimura, Phys. Plasmas **9**, 4637 (2002).
  - Viscosities depend on the 3 transport coefficients (D_{11}, D_{13}, D_{33}) already calculated by DKES
  - QPS poliodal viscosity reduced by a factor of 4-6 over the equivalent tokamak.
  - Potential use as an optimization target

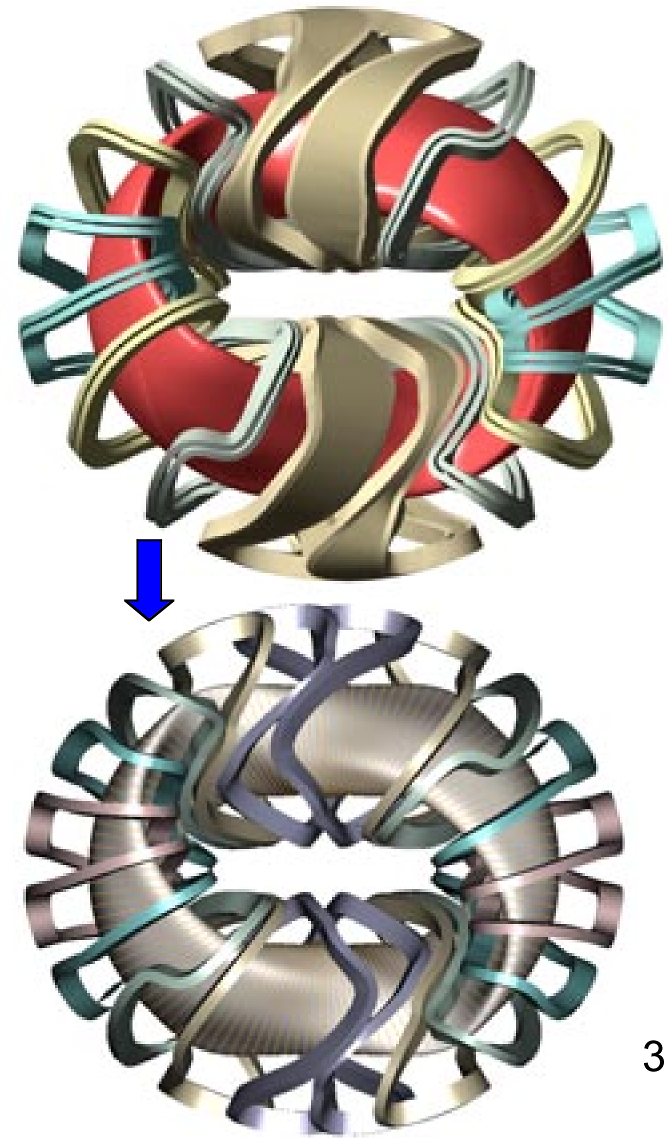
Previous QPS modular coils (January, 2003)
32 winding packs, 4 distinct coils



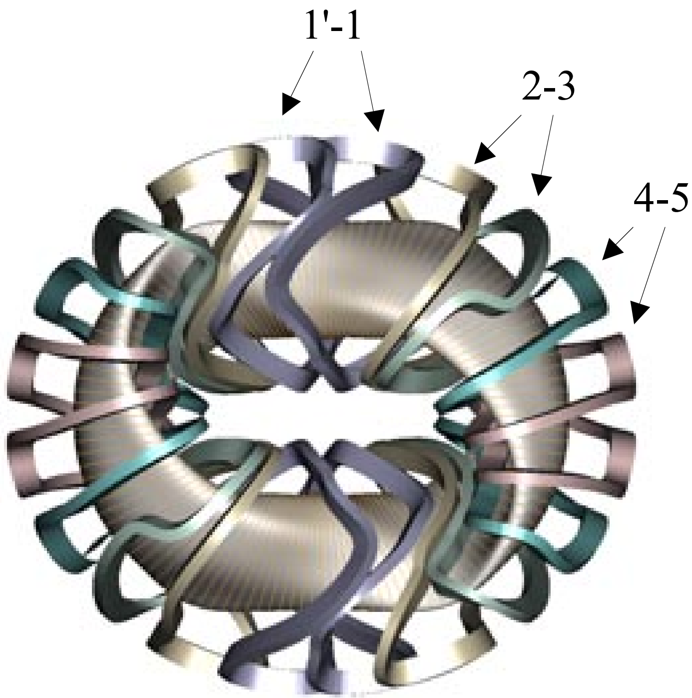


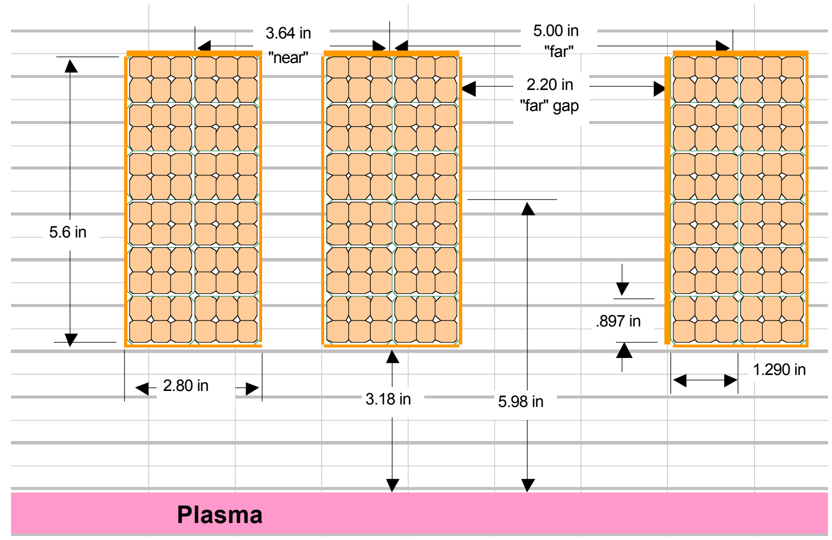
A re-configuration of the QPS modular coils - together with changes in the COILOPT coil separation targets – has led to a design with improved engineering feasibility and reduced cost

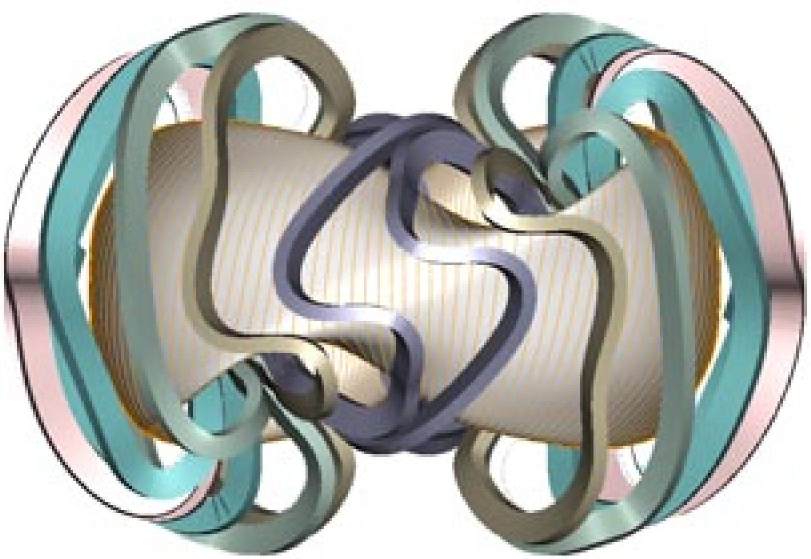
- All modular coils are combined in pairs with variable web
- Number of distinct winding form types reduced from 4 to 3
- Number of winding packs decreased from 32 to 20
- Increase min. distance between ‘unpaired’ coils from 9.6 to 13 cm
- Min. coil radius of curvature increased from 9.3 to > 12.2 cm
- Min. distance across the center of the torus increased by 4 cm

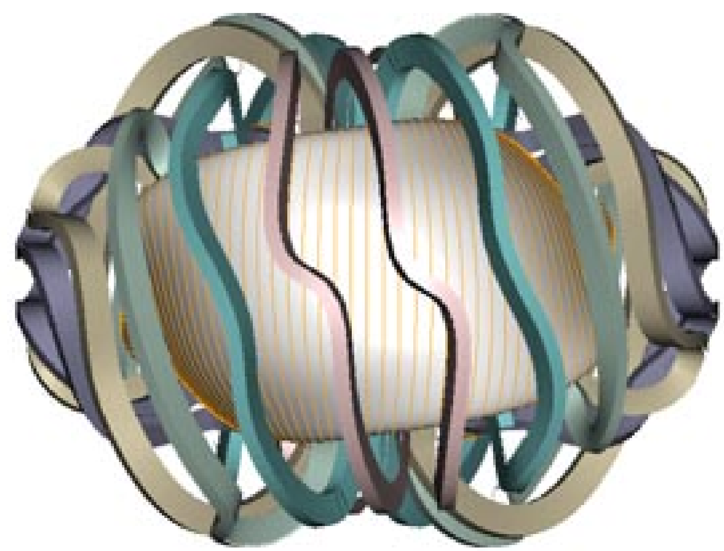


A re-configuration of QPS coils reduces the number of modular coil winding form types to 3









A new vacuum field constraint in the STELLOPT / COILOPT code has led to a robust class of Quasi-Poloidal compact stellarator configurations

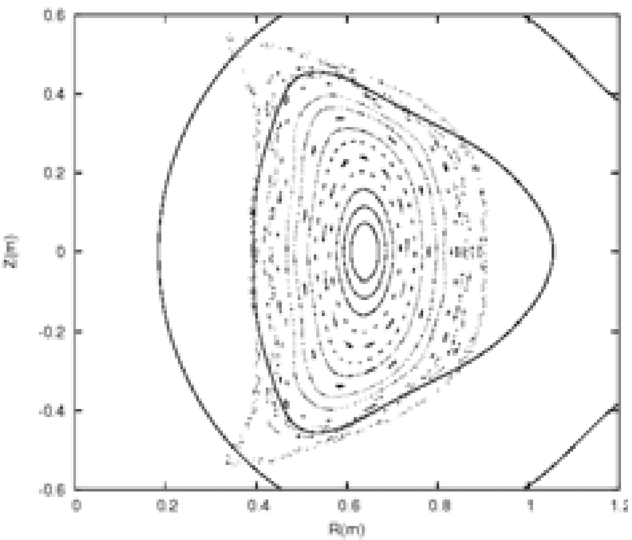
- Previously, plasma surface shape/quality was only optimized at the full design β
  - No guarantee of good surfaces at low/intermediate β's
  - One could do the optimization at low β, but then would lose control over ballooning stability
- Compromise: minimize the normal component of *vacuum* magnetic field error $\chi_B = w_B|B \cdot n||/|B|$ using the B field from the coils, but on the *full-pressure* plasma boundary shape.

- Forces vacuum surface to enclose similar volume as the full-pressure plasma

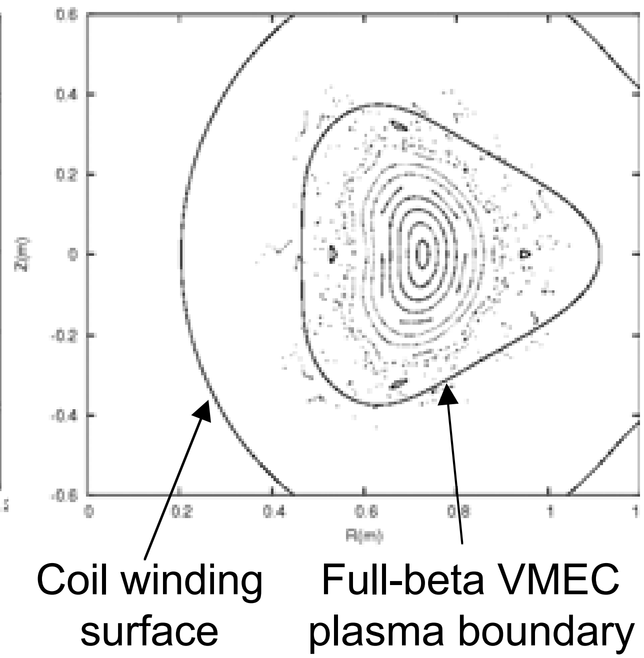
- Aspect ratio and shape are maintained as β is increased

QPS magnetic surface quality improvement

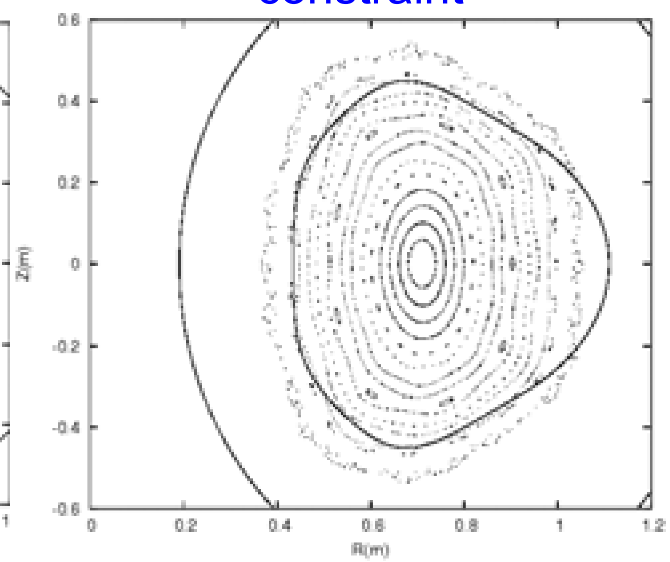
Full β plasma boundary and vacuum surfaces of QPS PAC configuration



Full β plasma boundary and vacuum surfaces of new QPS configuration before use of the vacuum constraint



Full β plasma boundary and vacuum surfaces of new QPS configuration after use of the vacuum constraint



Neoclassical viscous flow damping in QPS

- Recently Sugama, et al.[1] have adapted the moment method of Hirshman and Sigmar[2] to stellarator transport in a way that connects to transport coefficients provided by the DKES code
  - Uses fluid momentum balance equations and friction-flow relations that take into account momentum conservation
  - Viscosity coefficients are obtained from the drift kinetic equation
    - Uses l = 2 Legendre components of f (for which the test particle component of the collision term dominates over the field component)
    - Does not directly calculate Γ and Q from f because the field component of the collision operator is more significant for these moments
- Provides:
  - A way to assess viscosities in low aspect ratio quasi-symmetric devices
  - Momentum conserving corrections to DKES-based bootstrap currents, particle and energy flows.

[1]H. Sugama, S. Nishimura, Phys. Plasmas **9**, 4637 (2002).

[2]S. P. Hirshman, D. J. Sigmar, Nuclear Fusion **21**, 1079 (1981).

Relation of viscosities to DKES transport coefficients:

$$\text{Viscous Forces} \propto \begin{bmatrix} \left\langle \vec{B}_P \cdot \left(\vec{\nabla}\cdot\vec{\pi}\right)\right\rangle \\ \left\langle \vec{B}_T \cdot \left(\vec{\nabla}\cdot\vec{\pi}\right)\right\rangle \end{bmatrix} = \begin{bmatrix} M_{1PP} & M_{1PT} \\ M_{1PT} & M_{1TT} \end{bmatrix} \begin{bmatrix} \left\langle u^\theta \right\rangle / \chi' \\ \left\langle u^\xi \right\rangle / \psi' \end{bmatrix}$$

where: $\vec{\pi}$ = viscous stress tensor, u^θ, u^ξ = contravariant poloidal/toroidal flow velocities
(the heat flux terms in the above equation have not been indicated for simplicity)

$$M_{1PP},\ M_{1PT},\ M_{1TT} = \frac{2n}{\sqrt{\pi}} \int_0^\infty dK \sqrt{K} e^{-K} \left(K - \frac{5}{2}\right) \left[M_{PP}(K),\ M_{PT}(K),\ M_{TT}(K)\right]$$

where $K = m\mathrm{v}^2/2kT$ and

$$\begin{bmatrix} M_{PP} & M_{PT} \\ M_{PT} & M_{TT} \end{bmatrix} = \frac{4\pi^2}{V'} \begin{bmatrix} \chi' B_\theta / \left\langle B^2 \right\rangle & -\frac{e}{c}\psi'\chi' \\ \psi' B_\theta / \left\langle B^2 \right\rangle & \frac{e}{c}\psi'\chi' \end{bmatrix} \begin{bmatrix} M & N \\ N & L \end{bmatrix} \begin{bmatrix} \chi' B_\theta / \left\langle B^2 \right\rangle & \psi' B_\theta / \left\langle B^2 \right\rangle \\ -\frac{e}{c}\psi'\chi' & \frac{e}{c}\psi'\chi' \end{bmatrix}$$

We choose the following normalizations (following Sugama, et al.) for the viscosities:

$$\mathrm{M}^* = \frac{M}{m\mathrm{v}_T K^{3/2}} = \frac{(\nu/\mathrm{v}) D_{33}^*}{1 - \frac{3}{2}\frac{\nu}{\mathrm{v}} D_{33}^* / \left\langle B^2 \right\rangle} \qquad L^* = \left(\frac{e}{c}\right)^2 \frac{L}{m\mathrm{v}_T K^{3/2}} = D_{11}^* - \frac{2}{3}\frac{\nu}{\mathrm{v}} \left\langle \tilde{U}^2 \right\rangle \frac{\frac{3}{2}\frac{\nu}{\mathrm{v}} \left(D_{13}^*\right)^2 / \left\langle B^2 \right\rangle}{1 - \frac{3}{2}\frac{\nu}{\mathrm{v}} D_{33}^* / \left\langle B^2 \right\rangle}$$

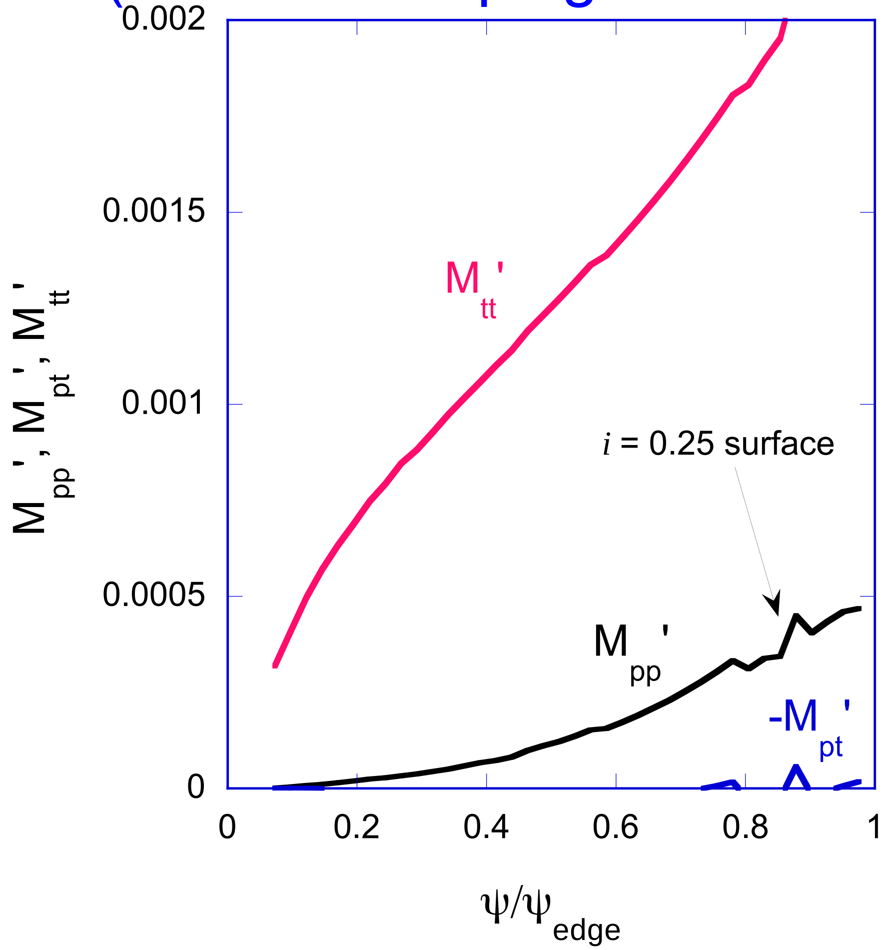
$$N^* = \frac{e}{c} \frac{N}{m\mathrm{v}_T K^{3/2}} = \frac{(\nu/\mathrm{v}) D_{13}^*}{1 - \frac{3}{2}\frac{\nu}{\mathrm{v}} D_{33}^* / \left\langle B^2 \right\rangle}$$

where the normalized transport coefficients below are in the form generated by DKES:

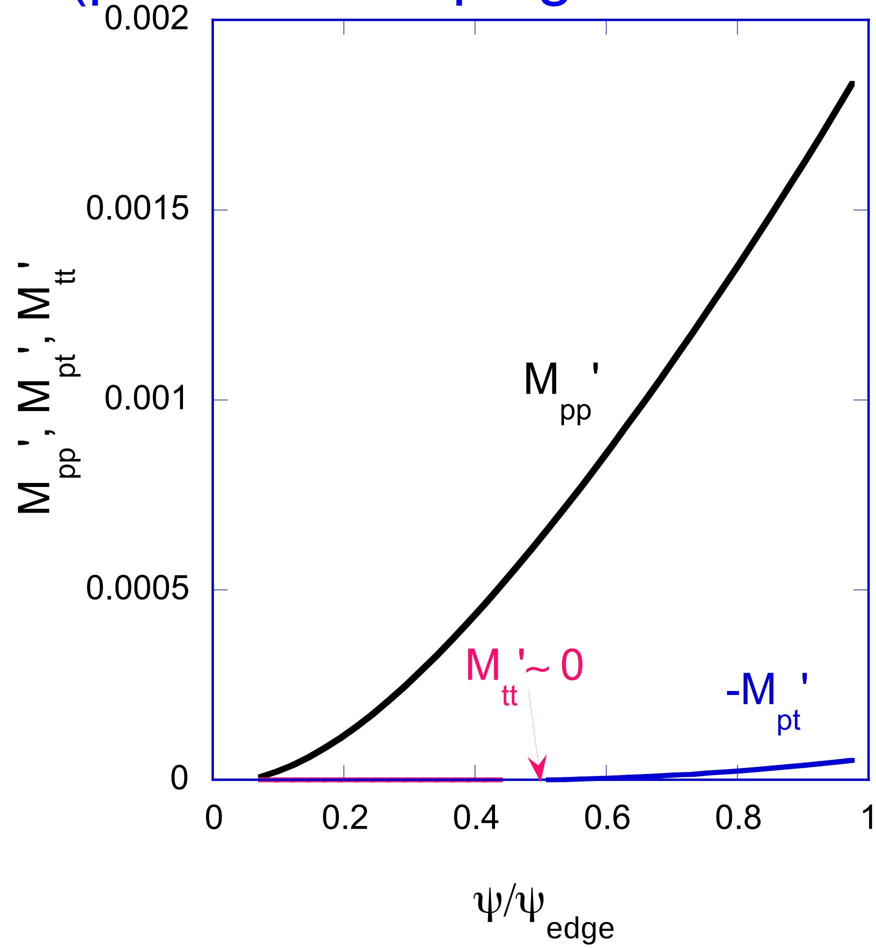
$$D_{11}^* = D_{11} / \left[\frac{1}{2}\mathrm{v}_T \left(\frac{B\mathrm{v}_T}{\Omega}\right)^2 K^{3/2}\right], \quad D_{13}^* = D_{13} / \left[\frac{1}{2}\mathrm{v}_T \left(\frac{B\mathrm{v}_T}{\Omega}\right) K\right], \quad D_{33}^* = D_{33} / \left[\frac{1}{2}\mathrm{v}_T K^{1/2}\right]$$

Quasi-poloidal symmetry leads to a factor of 4 - 6 reduction in the poloidal viscosity (M'_{pp}) over the equivalent tokamak configuration (at $E_r = 0$, $\nu/v = 0.01$)

QPS Viscosities (toroidal damping dominates)

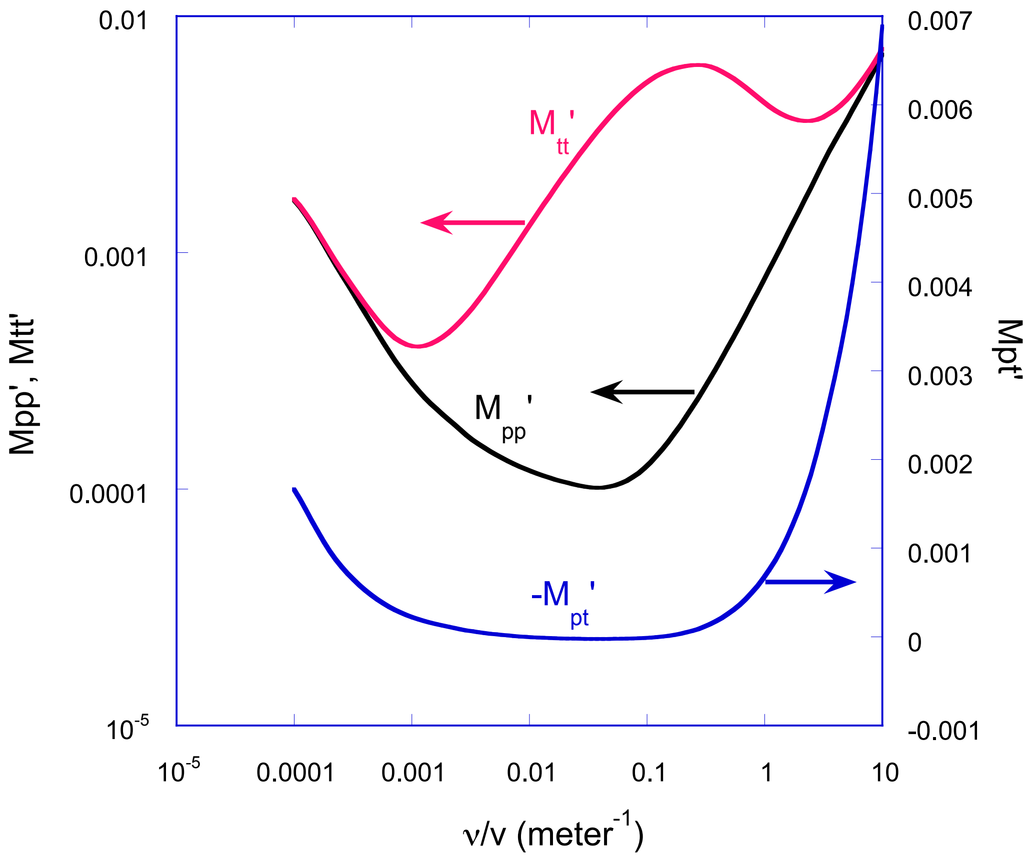


Equivalent Tokamak Viscosities (poloidal damping dominates)



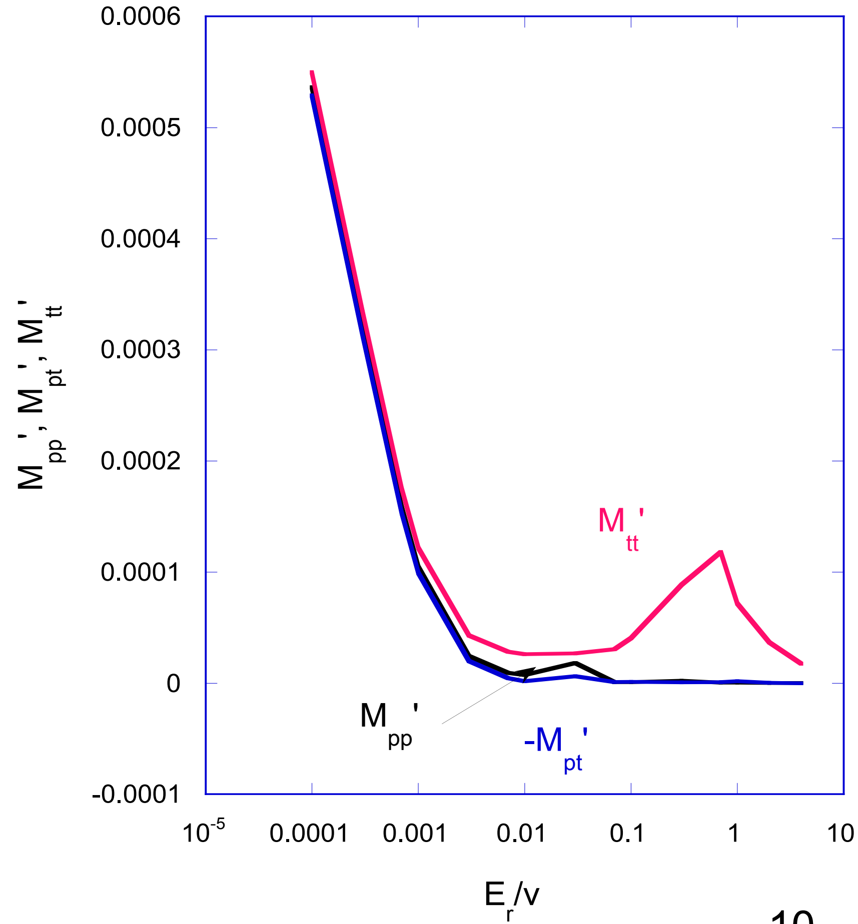
Collisionality dependence of QPS viscosities

(at ψ/ψ_{edge} = 0.5, E_r = 0)



E_r dependence of QPS viscosity

(at ψ/ψ_{edge} = 0.5, ν/v = 0.01)



Momentum conserving corrections to DKES particle/energy transport coefficient:

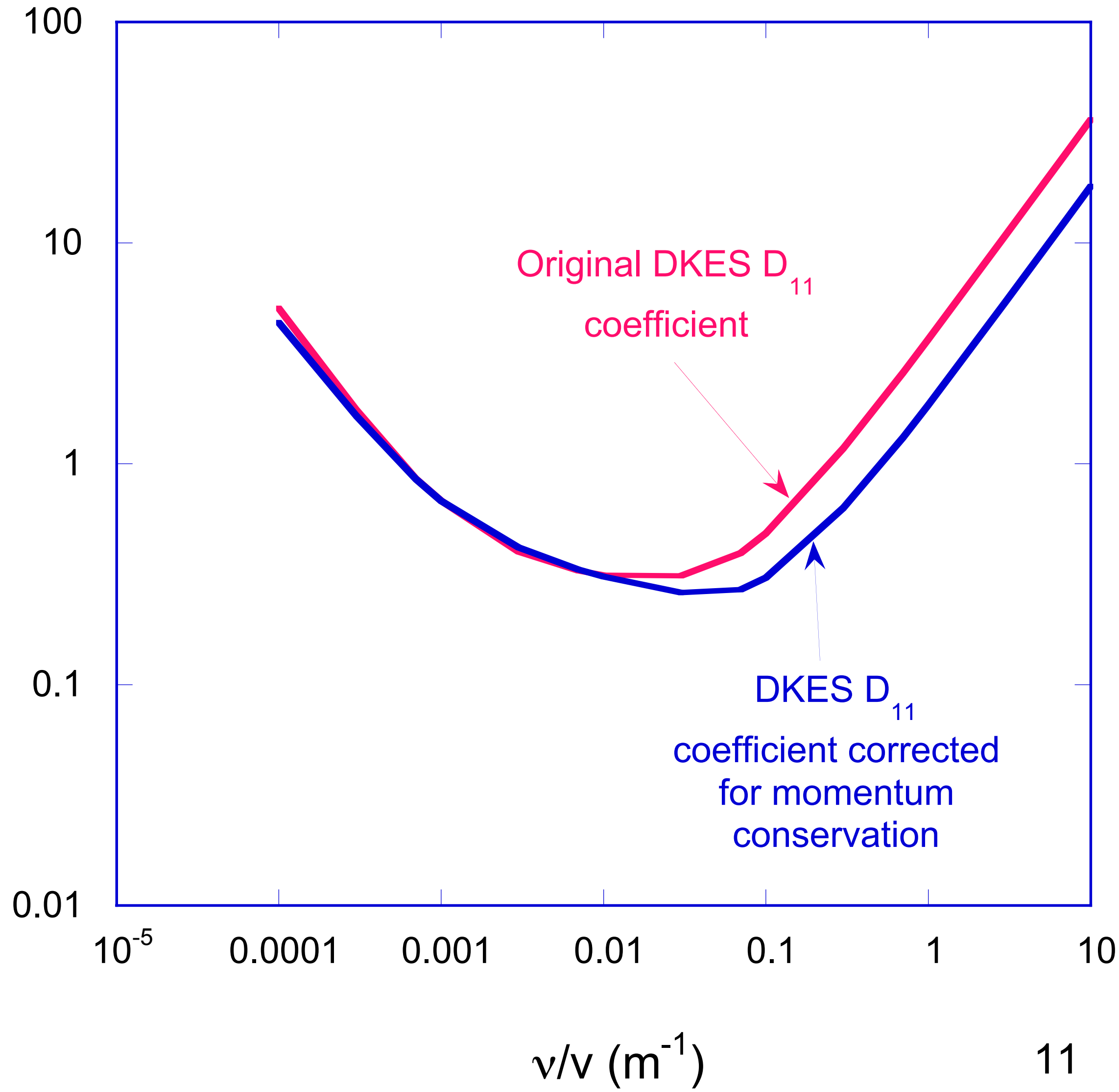
The parallel viscosity and radial flows are given by:

$$\begin{bmatrix} \left\langle \vec{B} \cdot \left(\vec{\nabla} \cdot \vec{\pi} \right) \right\rangle \\ \Gamma \end{bmatrix} = \begin{bmatrix} M_1 & N_1 \\ N_1 & L_1 \end{bmatrix} \begin{bmatrix} \dfrac{\langle u_{\parallel} B \rangle}{\langle B^2 \rangle} \\ -\dfrac{1}{n}\dfrac{\partial p}{\partial s} - e\dfrac{\partial \phi}{\partial s} \end{bmatrix}$$

where

$$\left(M_1,\ N_1,\ L_1\right) = \frac{2nm\mathrm{v}_T}{\sqrt{\pi}} \int_0^{\infty} dK \sqrt{K} K^{3/2}$$

$$\times \left[M^*(K),\ \left(\frac{c}{e}\right) N^*(K),\ \left(\frac{c}{e}\right)^2 L^*(K) \right]$$



The formulation of Sugama, et al. is useful for the post-processing of DKES transport coefficients:

- Lowered damping of poloidal flows should allow:
  - Generation of ambipolar transport-driven equilibrium poloidal ExB sheared flows
  - Generation of dynamical, Reynold's stress driven sheared flows possibly at lower power thresholds.
  - Both effects can potentially aid in break-up of turbulent eddies (predominantly 2D) allowing access to enhanced confinement regimes
- Development of a poloidal viscosity optimization target
- Momentum conserving corrections to DKES particle/energy transport and bootstrap current coefficients.